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The Magellanic impact: Collision between the outer Galactic H I disk and the leading arms of the Magellanic stream

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ABSTRACT

We show that collisions between the outer Galactic H I disk and the leading arms (LAs) of the Magellanic stream (MS) can create giant H I holes and chimney-like structures in the disk. Based on the results of our N-body simulations on the last 2.5 Gyr evolution of the Large and Small Magellanic Clouds (LMC and SMC, respectively) interacting with the Galaxy, we investigate when and where the LAs can pass through the Galactic plane after the MS formation. We then investigate hydrodynamical interaction between LAs and the Galactic H I disk ("the Magellanic impact") by using our new hydrodynamical simulations with somewhat idealized models of the LAs. We find that about 1-3% of the initial gas mass of the SMC, which consists of the LAs, can pass through the outer part ($R = 20 - 35$ kpc) of the Galactic H I disk about 0.2 Gyr ago. We also find that the Magellanic impact can push out some fraction ($\sim 1\%$) of the outer Galactic H I disk to form 1-10 kpc-scale H I holes and chimney-like bridges between the LAs and the disk.

Subject headings: Magellanic Clouds – galaxies:structure – galaxies:kinematics and dynamics – galaxies:halos

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1. Introduction

H I gas in the Magellanic stream, its leading arms, and the Magellanic bridge have long been discussed in the context of dynamical and hydrodynamical interaction between the Magellanic Clouds (MCs) and the Galaxy (e.g., Murai & Fujimoto 1980; Putman et al. 1998; Mastropietro et al. 2005; Muller & Bekki 2007). Such intense interactions between the three galaxies have been also suggested to be closely associated not only with the long-term star formation histories of the LMC and the SMC (e.g., Harris & Zaritsky 2004; Cioni et al. 2006) but also with structural and kinematical properties of the MCs (e.g., Bekki & Chiba 2005, BC05). It is however not fully understood how the interactions can change dynamical and chemical properties and star formation histories of the MCs (e.g., Westerland 1997).

Although many previous numerical/theoretical works discussed influences of the Galaxy on the evolution of the MC (e.g., Gardiner & Noguchi 1995; BC05; Růžička et al. 2007), only a few works investigated the possible gravitational influences of the MCs on the dynamical evolution of the Galactic *the stellar disk* (e.g., Weinberg 1998; Tsuchiya 2002) and the gaseous one (Weinberg & Blitz 2006). For example, these works discussed whether the observed Galactic warp can be due to the dynamical interaction between the LMC and the Galaxy (e.g., Tsuchiya 2002). Although previous numerical and observational studies on the MS formation suggested possible interaction between the LAs and the Galaxy (e.g., Yoshizawa & Noguchi 2003; Brüns et al. 2005; Connors et al. 2006), the details of the interaction processes have not been investigated yet. In particular, it is totally unclear *how the gaseous components of the Galaxy are influenced by the gaseous components of the MCs.*

Recent observational studies on the physical properties of the outer H I disk of the Galaxy have reported a significant (~ 10 km s^{-1}) velocity perturbation in the outer H I spiral arm of the Galaxy at $l = 275^{\circ} - 295^{\circ}$ (McClure-Griffiths et al. 2004, M04). Furthermore, it remains unclear why the outer H I disk ($19 < R < 28$ kpc) appears to show significantly lower densities between the Galactic longitudes $l = 285^{\circ}$ and 300° (See Figure 2 in M04). No theoretical works have however discussed so far the origin of these unique properties in M04.

The purpose of this Letter is to show, for the first time, how collision between the LAs and the Galactic H I disk (hereafter referred to as "the Magellanic impact") influences the evolution of the Galactic H I disk. We first show when and how the LAs can pass through the Galactic disk based on our collisionless N-body simulations on the evolution of the MCs for the last 2.5 Gyr (e.g., Bekki & Chiba 2007, BC07). We then show that the Magellanic impact can create unique, kpc-scale H I holes and chimney-like bridges connecting the LAs and the outer part of the Galactic H I disk based on new yet somewhat idealized hydrodynamical simulations on the Magellanic impact.

2. The two-fold model

The present investigation is two-fold as follows. We first investigate when and where the LAs can pass through the Galaxy during the LMC-SMC-Galaxy interaction based on purely collisionless N-body simulations similar to our previous ones (BC07). In this first investigation, we focus exclusively on the locations and the masses of the LAs at the epochs of LAs' passage through the Galactic disk, because previous models did not clearly describe these. We then investigate how the Magellanic impact influences the outer part of the Galactic H I disk for a reasonable set of initial conditions of the Magellanic impact derived by the above first investigation by using our new hydrodynamical simulations. Since numerical methods and techniques for the first collisionless N-body simulations and the second GRAPE-SPH ones are already given in BC07 and Bekki & Chiba (2006), respectively, we here briefly describe them.

2.1. The LA formation

We first determine the most plausible and realistic orbits of the MCs by using " the backward integration scheme" (for orbital evolution of the MCs) by Murai & Fujimoto (1980) for the last 2.5 Gyr and then perform the first set of collisionless N-body simulations on the evolution of the MCs using GRAPE systems (Sugimoto et al.1990). The total masses of the LMC and the SMC are set to be $2.0 \times 10^{10} \mathrm{M}_{\odot}$ and $3.0 \times 10^{9} \mathrm{M}_{\odot}$, respectively, in all models. The SMC is represented by a fully self-consistent dynamical model composed of a dark matter halo, a stellar disk or spheroid, and a gas disk whereas the LMC is represented by a point mass.

The mass fraction of the baryonic component (i.e., stars and gas) and the gas mass fraction of the baryon in the SMC are considered to be free parameters and represented by f_{b} and f_{g}, respectively. The ratio (s) of the gas disk size ($R_{\mathrm{g,SMC}}$) to the stellar one ($R_{\mathrm{s,SMC}}$) in the SMC is also considered to be a free parameter that can effect the morphologies of the MS and the LAs. Although we have investigated models with different f_{b}, f_{g}, $R_{\mathrm{g,SMC}}$, and s, we focus on the results of a LA model with $f_{\mathrm{b}} = 0.33$, $f_{\mathrm{g}} = 0.20$, $R_{\mathrm{g,SMC}} = 7.5$ kpc, and $s = 4.0$: Results of the other models will be given in our future papers (Bekki & Chiba in preparation). This model is simply referred to as the LA model.

We use the same coordinate system (X, Y, Z) (in units of kpc) as those used in BC05 and BC07. The adopted current positions are $(-1.0, -40.8, -26.8)$ for the LMC and $(13.6, -34.3, -39.8)$ for the SMC and the adopted current Galactocentric radial velocity of the LMC (SMC) is 80 (7) km s^{-1}. Current velocities of the LMC and the SMC in the Galactic (U, V, W) co-

ordinate are assumed to be (-5,-225,194) and (40,-185,171) in units of km s^{-1}, respectively. As shown by previous studies (e.g., Gardiner & Noguchi 1995), the MS and the LAs can be formed for the adopted orbits of the MC. We do not intend to investigate the models with initial velocities consistent with the latest proper motion data (e.g., Kallivayalil et al. 2006). We investigate the accretion rate ($\dot{m}_{\rm SMC,g}$) of the SMC's gas particles initially in the LA onto the outer part of the Galaxy, the total masses of the LAs passing though the Galactic disk ($m_{\rm LA}$), the epochs of the passage ($T_{\rm LA}$), and the inclination angles of the LAs with respect to the Galactic disk at $T = T_{\rm LA}$ ($\theta_{\rm LA}$).

2.2. The tube model for the Magellanic impact

We investigate hydrodynamical interaction between the LAs and the outer part of the Galactic H I disk for models with different initial properties of the LAs (e.g., $m_{\rm LA}$ and $\theta_{\rm LA}$) derived by the first set of collisionless simulations of the LA formation. In this second set of GRAPE-SPH simulations, the gaseous stream of the LA is assumed to be represented by a long "tube" with a size of $r_{\rm LA}$, a length of $l_{\rm LA}$, a mass of $m_{\rm LA}$, a position (with respect to the Galactic center) of $\mathbf{x}_{\rm LA}$, an inclination angle of $\theta_{\rm LA}$, and a velocity of $v_{\rm LA}$ (≥ 0). We adopt the ring model (BC06) for the outer part (20 kpc $\leq R \leq$ 40 kpc) of the Galactic H I disk with a uniform distribution so that we can focus solely on the evolution of *the outer part* of the Galactic H I disk during the Magellanic impact. Considering the observational fact that the total H I mass of the Galaxy is about $4 \times 10^9 {\rm M}_{\odot}$ (e.g., van der Kruit 1989), the total gas mass of the ring for 20 kpc $\leq R \leq$ 40 kpc is assumed to be $1.4 \times 10^9 {\rm M}_{\odot}$. We assume that the size of the stellar disk of the Galaxy ($R_{\rm s,MW}$) is 17.5 kpc and that the Galaxy is composed only of gas outside $R_{\rm s,MW}$.

We here discuss the results of two representative models, Model A and B, among those that we have investigated. Firstly we show the result of the Model A with $r_{\rm LA} = 2.1$ kpc, $l_{\rm LA} = 21$ kpc, $m_{\rm LA} = 10^7 {\rm M}_{\odot}$, $\mathbf{x}_{\rm LA}$=(31.5 kpc, 0 kpc, -10.5 kpc), $\theta_{\rm LA} = 60^{\circ}$, and $v_{\rm LA} = 393$ km s^{-1} in §3. We chose the above $\mathbf{x}_{\rm LA}$ so that we can show more clearly the evolution of the outer part of the Galactic disk projected onto the X-Y and X-Z planes: the adopted values are slightly different from the predicted locations of the LA. We then discuss the results of the Model B with $r_{\rm LA} = 2.1$ kpc, $l_{\rm LA} = 63$ kpc, $m_{\rm LA} = 10^8 {\rm M}_{\odot}$, $\mathbf{x}_{\rm LA}$=(21.0 kpc, -15.8 kpc, -10.5 kpc), $\theta_{\rm LA} = 60^{\circ}$, and $v_{\rm LA} = 314$ km s^{-1} in §4. This model can reproduce best the observations by M04.

3. Results

Figure 1 shows that the LAs composed mainly of two gaseous streams can pass through the Galactic plane about 0.2 Gyr (i.e., $T \sim -0.2$ Gyr) in the LA model. The high-density tip of the LA passes through the outer part ($R > 20$ kpc) of the Galaxy with a high $\theta_{\rm LA}$ (the inclination angle between the LA and the Galactic plane) and a high vertical velocity of $v_{\rm LA,z} = 240$ km s^{-1}. About 1.4 % of the inital gas particles of the SMC can pass though the outer region ($R_{\rm s,MW} \le R \le 2R_{\rm s,MW}$) for the last ~ 0.3 Gyr and the vertical velocities ($v_{\rm LA,z}$) of the gas particles in the LAs are rather high and range from 186 km s^{-1} to 317 km s^{-1}. The accretion rate $\dot{m}_{\rm SMC,g}$ reaches a peak at $T \sim -0.2$ Gyr with the peak value of $\sim 0.4{\rm M}_{\odot}$ yr^{-1}. It is found that the projected distribution of particles passing through the Galactic disk at $T \sim -0.2$ Gyr are well confined in the sense that most particles are located at -10 kpc $\le X \le -5$ kpc and at -20 kpc $\le Y \le -15$ kpc.

Figure 2 shows how the Magellanic impact changes the vertical structure of the outer part of the Galactic gas disk in the Model A. Although the Magellanic impact can not change the global structure of the Galactic gas disk (e.g., warps and spiral arms) owing to the adopted small mass of the LA ($m_{\rm LA} = 10^7{\rm M}_{\odot}$), it can push out a small fraction $\sim 1\%$) of the gas disk and form chimney-like bridges connecting the LA and the Galaxy. The bridges can be seen above the Galactic disk (i.e., $Z > 0$) not only in this Model A but also in other models, which is thus a robust prediction that can be tested against ongoing and future H I observations (e.g., M04 and McClure-Griffiths et al. 2006, M06). The gaseous particles in the bridges for 2 kpc $\le Z \le$ 10 kpc at $T = 164$ Myr have large (positive) vertical velocities (95 km s^{-1} on average) that are significantly different from those of the particles within the Galactic H I disk.

Figure 3 shows that as a result of the Magellanic impact, a giant H I hole with a size of ~ 10 kpc can be formed in the outer part ($R \sim 35$ kpc) of the Galactic H I disk. The H I hole can be neither destroyed nor significantly elongated owing to the shear motion of the Galactic gas disk within a time scale of 0.2 Gyr (i.e., the time interval between the Magellanic impact and the present) so that it can be clearly seen in the final snapshot of the model. Only the right part of the hole (i.e., $X \sim 30$ kpc and $Y \sim 22$ kpc) clearly shows a ridge with a significantly higher gas density ($\mu_{\rm g} \sim 0.8{\rm M}_{\odot}$ pc^{-2}). Such giant H I holes in the very *outer* part of the Galaxy are highly unlikely to form via feedback effects of massive stars and supernovae, because the rate of massive star formation at large radii is very low in such low density regions.

The surface gas densities along azimuthal angles ($\mu_{\rm g}(\theta)$) averaged over a range of 30 kpc $\le R \le$ 40 kpc in the Galactic disk are found to range from $0.16{\rm M}_{\odot}$ pc^{-2} to $0.48{\rm M}_{\odot}$ pc^{-2} with the mean of $\mu_{\rm g}(\theta)$ being $0.40{\rm M}_{\odot}$ pc^{-2} in this model. The minimum value is found

where the giant H I hole exists, which suggests that the line-of-sight column density (with respect to the Sun) in the direction to an H I hole can be a factor of $2-3$ smaller than those in other directions. We discuss these results in terms of observations by M04 later in §4. We confirm that the models with $m_{\rm LA} = 10^5 - 10^6 {\rm M}_{\odot}$ do not show any kpc-scale holes with remarkable chimney-like structures owing to the rather weak dynamical impacts of the LA on the Galactic H I disk.

4. Discussion and conclusions

We first have shown that the Magellanic impact can create 10kpc-scale H I holes and bridges connecting the LA and the Galaxy. The physical properties of the simulated unique structures in the outer part ($R \sim 30$ kpc) of the Galactic gas disk can be tested against previous and ongoing observational studies on H I properties of the Galaxy (e.g., M04; Levine et al. 2006; M06). Although detailed comparison of ongoing and future observations will be given in our future papers, here we briefly discuss previous observations shown in Figures 1 and 2 of M04 compared to the Model B in a more quantitative manner.

Figure 4 clearly shows the longitude-velocity ($l-v$) diagram of particles of the Galactic gas disk in the Model B, where v denotes the line-of-sight velocities of the particles with respect to the Sun. Clearly the $l-v$ diagram shows a bifurcation around at $l = 280^{\circ} - 300^{\circ}$, the most clearly at $l \sim 290^{\circ}$. This bifurcation is due to the dynamically disturbed gas disk of the Galaxy by the Magellanic impact and may correspond to a part of the observed significant (~ 10 km s^{-1}) velocity perturbation in the outer H I spiral arm of the Galaxy at $l = 275^{\circ} - 295^{\circ}$ (see Figure 1 of M04). Figure 4 also shows a significantly less populated region at $l = 280^{\circ} - 300^{\circ}$ in the particle distribution on the ($l-b$) plane owing to the presence of the giant H I hole there created by the Magellanic impact. This is broadly consistent with observations shown in Figure 2 of M04, which shows that the outer H I disk of the Galaxy shows significantly lower densities between the Galactic longitudes $l = 285^{\circ}$ and 300°.

Velocities of particles pushed out from the Galactic plane can be more than 50 km s^{-1} higher than those within the Galactic disk in Figure 4, which can not be seen in Figure 1 of M04. This apparent inconsistency possibly means that such high-velocity gas with low-density and low-mass ($\sim 10^3 {\rm M}_{\odot}$) can be soon changed into ionized gas owing to possible interaction with warm/hot halo gas of the Galaxy so that it can not be observed as H I. Although the observed $l-v$ diagram in M04 does not clearly show bifurcation, the H I seems to be distributed on two belts for $260^{\circ} < l < 295^{\circ}$ and $v > 60$ km s^{-1}. It remains observationally unclear whether this intriguing distribution can correspond to a bifurcated distribution of H I on the $l-v$ diagram.

The direction of the orbit of the LA (with respect to the Galaxy) can significantly change at the Galactic plane (i.e., $b = 0°$) as a result of hydrodynamical interaction between the LA and the Galactic H I disk. The orbital change at $b = 0°$ due to the back reaction of the Magellanic impact can explain why the observed distribution of the LA in the Galactic coordinate shows a "kink" at $b = 0°$ (e.g., Brüns et al. 2005). Furthermore the total H I mass of the LA can be significantly reduced by photoionization of the H I gas of the LA by the warm gas of the Galactic disk during the Magellanic impact. This significant reduction of the H I mass in the LA can solve the well known problem as to the observed small mass ratio (~ 0.2) of the LA to the MS (e.g., Brüns et al. 2005).

It is possible that the Magellanic impact can trigger some amount of star formation in the outer part of the Galactic gas disk owing to collisions between gas clouds from the Galaxy and those from the LA. We thus suggest that the presence (or the absence) of B-type stars with ages of $0.1 - 0.2$ Gyr at $270° < l < 300°$ and $b \sim 0°$ would prove (or disprove) the past star formation activities of the Galaxy induced by the Magellanic impact. We also suggest that hydrodynamical interactions between gaseous tidal tails and debris from disrupting low-mass galaxies (like the SMC) and outer parts of galactic H I disks can be proved by observations on detailed spatial distributions of H I in galaxies. In particular, future structural and kinematical studies on the observed giant H I holes in the very outer parts of galaxies (e.g., NGC 6822; de Blok & Walater 2003) will allow us to discuss whether or not hydrodynamical interaction between gaseous tidal tails and outer gas disks of galaxies can be important for the evolution of the outer disks.

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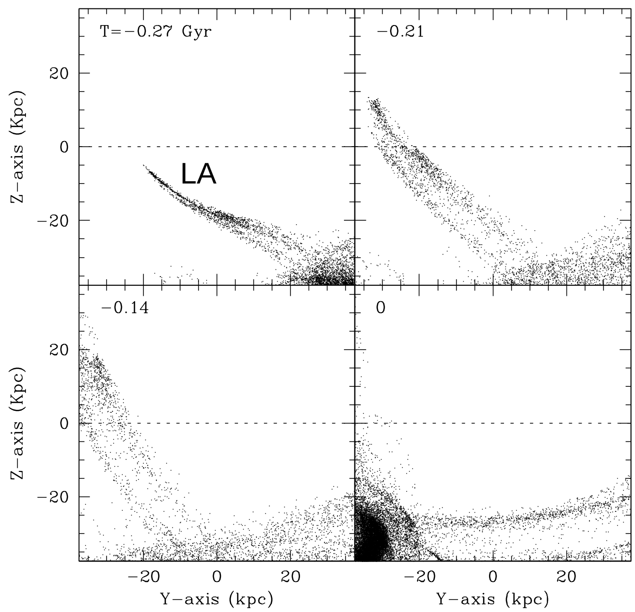

Fig. 1.— Time evolution of the LAs of the MS projected onto the Y-Z plane for the last 0.27 Gyr in the LA model. $T = 0$ means the present while the negative T means the past (e.g., $T = -0.27$ means 0.27 Gyr ago). The locations of the tips of the LAs are marked by "LA" for clarity. The dotted line in each panel represents the Galactic plane (i.e., $l = 0°$). Only particles that are within 75 kpc from the Galactic center are shown so that the evolution of the LAs can be much more clearly seen (owing to a smaller particle number). Note that the LAs composed of two streams can pass through the Galactic plane around 0.21 Gyr ago.

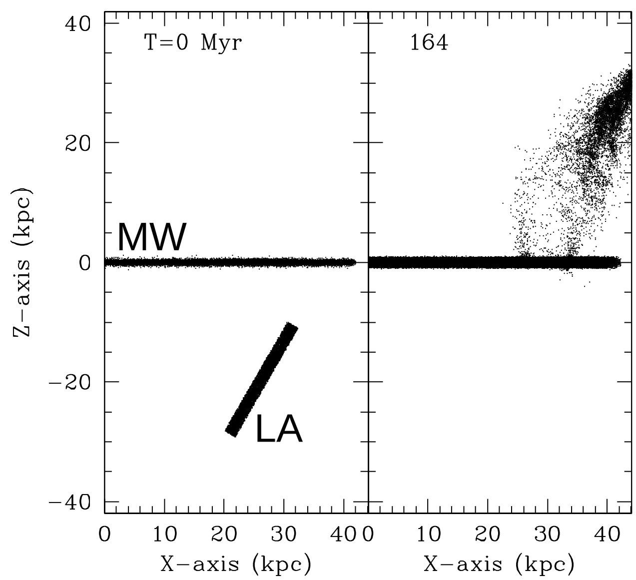

Fig. 2.— The initial (left) and final (right) distributions of gas projected onto the X-Z plane in the Model A for the last ~ 164 Myr. For convenience, the time T in this second set of simulations represents the time that has elapsed since the simulation starts (Note that the time definition is different from that used in Figure 1). It should be stressed here that the initial location (and configuration) of the LA with respect to the Galactic disk is chosen such that the physical effects of the Magellanic impact can be more clearly seen in this idealized model: The adopted initial location of the LA is not exactly the same as that predicted in the model shown in Figure 1.

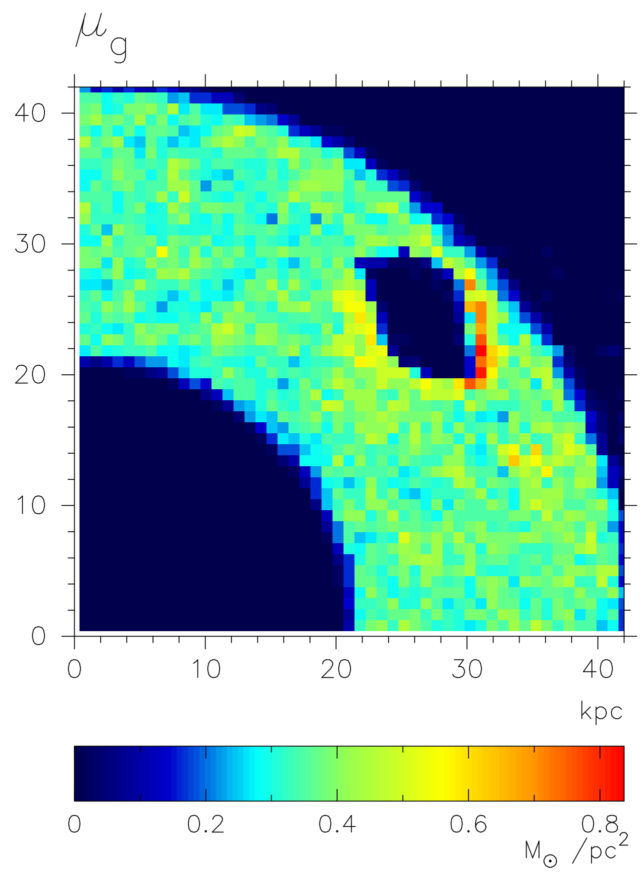

Fig. 3.— The two-dimensional surface gas density distribution ($\mu_{\rm g}$) of the outer H I disk of the Galaxy projected onto the X-Y plane in the Model A at T = 197 Myr (corresponding roughly to the present distribution of the Galactic H I gas after the Magellanic impact ~ 0.2 Gyr ago). Only gaseous particles initially in the H I disk of the Galaxy are shown so that $\mu_{\rm g}$ of the disk can be more clearly seen. A giant H I hole with a high-density ridge in the right side of the hole can be clearly seen.

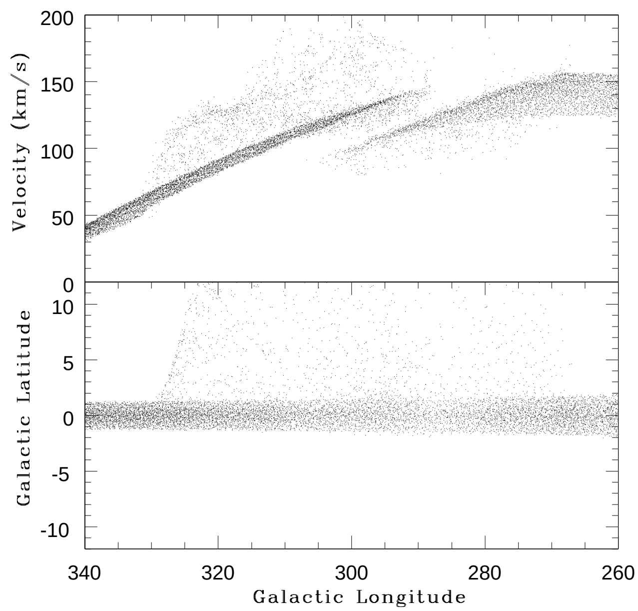

Fig. 4.— The simulated H I longitude-velocity $(l - v)$ diagram (upper) and the distribution of gas particles on the $(l - b)$ plane (lower) for the Model B in the present study. Only gas particles located in the outer Galactic gas disk (19 kpc $\leq R \leq$ 28 kpc) are selected so that the results can be more consistent with observations shown in Figures 1 and 2 of M04.